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Experimentally Determined Performance of Some Residential Circuit Breakers

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

Laboratory test results show that at low ambient temperatures some residential-type circuit breakers may not trip at currents up to 140 percent of rated currents. Under some environmental conditions this may lead to wiring temperatures that exceed the limitations specified in the National Electrical Code. The results also show that circuits sometimes open at the point of short circuits before circuit breakers operate. Ignition of combustibles proximate to the point of such short circuits sometimes occurs.

The results indicate the need for a more detailed study of overcurrent protection performance in the field and under laboratory conditions. Also needed are the development of more meaningful scientific/mathematical principles and models on the functional characteristics of circuit breakers.

Key Words: branch circuits; circuit breaker; electrical fire; low ambient temperature; trip time.

SI CONVERSION UNITS

In view of the present accepted practice in this country for building technology, common U.S. units of measurement have been used throughout this document. In recognition of the position of the United States as a signatory to the General Conference on Weights and Measures, which gave official status to the metric SI system of units in 1960, assistance is given to the reader interested in making use of the coherent system of SI units by giving conversion factors applicable to U.S. units used in this document.

Mass 1 pound-mass (lb_m) = 0.453592 Kg
Length 1 inch = 0.0254 meter (m)
Temperature t (Celsius) = 5/9[t(Fahr)-32]
Torque .1 Lbf.in = 0.113 newton meter (N•m)
Time 1 hour = 60 minutes = 3,600 seconds

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1. INTRODUCTION

The National Electrical Code (NEC) [1]* states that a circuit breaker is a device designed to open and close a circuit by nonautomatic means through manual operation of the device and to open the circuit automatically at or beyond a predetermined overcurrent without damage to itself or to protected electrical circuits when properly applied within its rating. An overcurrent is defined as any current in excess of the rated current of equipment conductors. Overcurrents may result from overloads, short circuits, or ground faults [1].

1.1 SCOPE

This investigation presents results from laboratory testing of residential type, single-pole, 20 A, thermal-magnetic circuit breakers. Standard 20 A plug fuses were tested for comparison with circuit breaker performance.

1.2 BACKGROUND

The need for circuit breaker research became apparent during recent investigations of temperatures produced by self-heating of wiring when surrounded by thermal insulation [2]. During that investigation it was recognized that circuit breakers do not quickly open circuits that are subjected to overcurrents. Circuit breakers are widely utilized in buildings because of the simplicity of resetting following operation on overloaded circuits without replacement, as in the case of fuses.

The Underwriters' Laboratories Standard, UL 489, for molded-case circuit breakers requires circuit breakers to open circuits within one hour at 135 percent of their rated current [3]. The UL standard requires this one-hour performance with an ambient temperature of 25°C (77°F). The standard does not include criteria for lower ambient air temperatures. The National Electrical Manufacturers Association (NEMA) standard for molded-case circuit breakers considers circuit breaker operation at under 0°C ambient temperature as unusual service conditions that should be brought to the attention of the manufacturer [4]. The standard does not present details concerning circuit breaker performance at 0°C or below.

A further impetus for circuit breaker research was provided during NBS laboratory short circuit experimentation with branch circuit wiring systems. It was observed that circuit breakers did not always open during short circuits. It was found that the circuits opened at a contact interface such as that between the circuit conductor and a shorting nail. The opening of the circuit in this manner was often accompanied by the expulsion of molten metal particles from the nail and/or conductor interface. Such performance might cause ignition of proximate combustibles. Neither the literature nor the circuit breaker standards appear to address this type of circuit breaker performance per se.

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* References cited at end of text.

1.3 LITERATURE SEARCH

A search of the technical literature revealed a UL Bulletin of Research [5] which addresses ambient temperature effects on circuit breakers. UL research was carried out because field reports to UL indicated that overcurrent devices sometimes failed to open circuits when subjected to moderate overloads and low ambient temperatures. The UL Bulletin as listed in reference [5] showed that both circuit breakers and plug fuses of 15 A rating oftentimes did not open the test circuits when tested at 135 percent of rated current at ambient temperatures of 32, 0, -10, -20, and -30°F. The UL Bulletin does not have a conclusion section per se [5]; however, the abstract states the following:

> "These findings confirm a view previously held that thermally operated devices are affected by the ambient temperature at which they are operated, and this should be taken into account in actual practice."

The UL circuit breaker and plug fuse tests were carried out over thirty years ago; NBS found no recent tests reported in the literature. The NBS tests presented in this report were carried out to gain insight into the low temperature performance of modern residential single-pole circuit breakers.

The literature search did not reveal studies concerning residential circuit breaker performance during short circuits. The literature contained very little information concerning the scientific/mathematical principles of residential circuit breakers; mathematical models for these breakers were not found in the literature.

1.4 FUNCTIONAL DESCRIPTION OF A THERMAL-MAGNETIC CIRCUIT BREAKER

Residential circuit breakers are usually of the molded-case type. A molded-case circuit breaker is one that is assembled as an integral unit in a housing of molded insulating materials [6]. The typical molded-case circuit breaker is equipped with both time-delay and instantaneous tripping devices [6].

Time-delay tripping has inverse time characteristics. This means that as the overload increases, the tripping time decreases. This results in the following performance.

a. The circuit breaker accepts short-duration overloads for motor starting.

b. During a large overcurrent or a short circuit, the circuit breaker is intended to trip rapidly to protect circuit conductors and electrical insulation from overheating.

The NEC defines several terms applying to circuit breakers [1]. These are as follows:

a. Adjustable: A qualifying term indicating that the circuit breaker can be set to trip at various values of current and/or time within a pre-determined range.

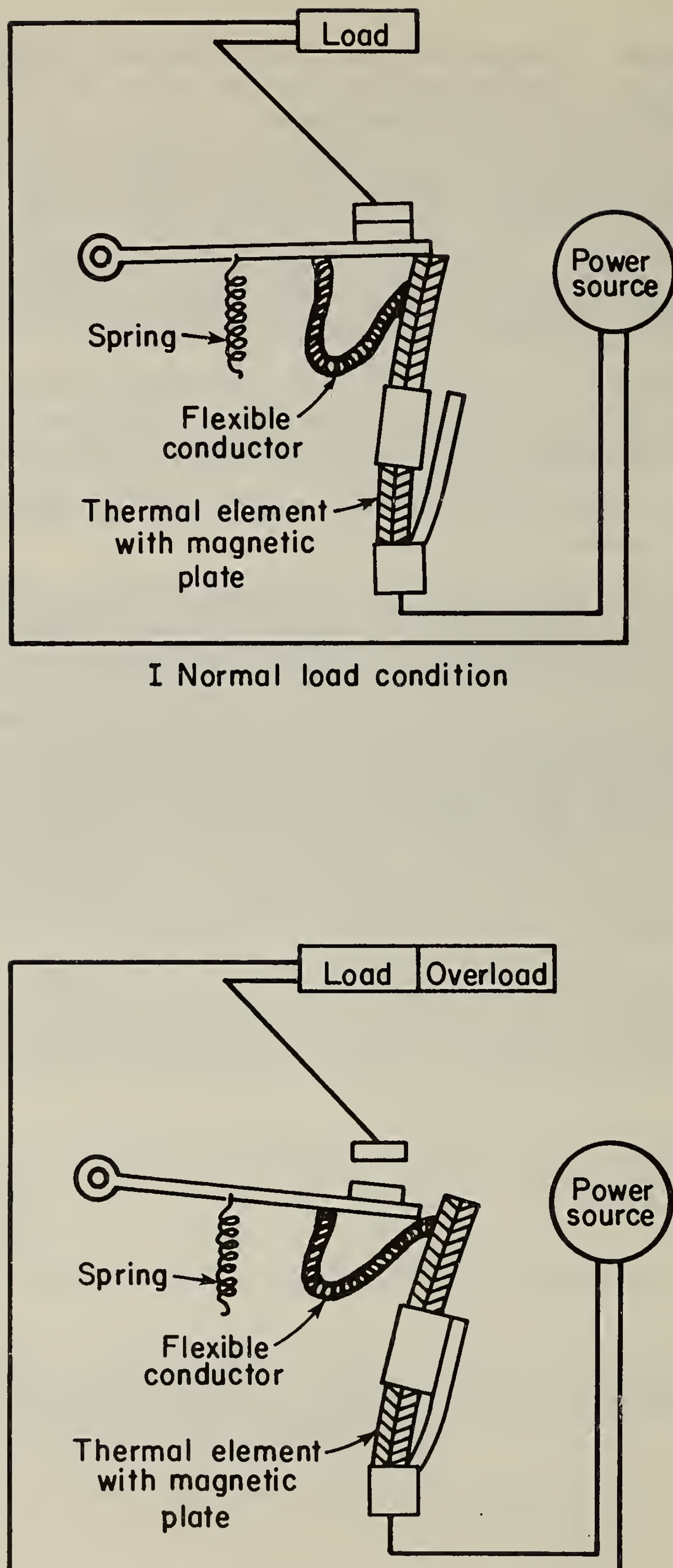
b. Instantaneous Trip: A qualifying term indicating that no delay is purposely introduced in the tripping action of the circuit breaker.

c. Inverse Time: A qualifying term indicating there is purposely introduced a delay in the tripping action of the circuit breaker, which delay decreases as the magnitude of the current increases.

d. Nonadjustable: A qualifying term indicating that the circuit breaker does not have any adjustment to alter the value of current at which it will trip or the time required for its operation.

e. Setting: The value of current and/or time at which an adjustable circuit breaker is set to trip.

Most residential circuit breakers of 15 A and 20 A size are single pole, inverse time, and nonadjustable. Residential circuit breakers of this size usually operate by thermal-magnetic means. The operation of a thermal magnetic breaker is depicted in figure 1 [7], which shows the release or tripping element. The element consists of a thermal, bimetallic element to which a magnetic plate has been added. During slight overcurrents, the magnetic force produced by the magnetic plate is so slight that it contributes little force to trip the circuit breaker, and the circuit breaker trips primarily because of the force generated by the heating of the bimetallic element. With high short-circuit currents, the magnetic tripping force predominates.



II Overload

Figure 1. Principle of thermal-magnetic breaker [7]

2. CIRCUIT BREAKER PERFORMANCE WITH SLIGHT TO MODERATE OVERCURRENTS AT VARIOUS AMBIENT TEMPERATURES

The purpose of the investigation reported upon in this section is to determine whether or not circuit breakers will trip during overcurrents when the circuit breaker is located in cool ambient air, such as might exist in a basement.

2.1 CIRCUIT BREAKER/TEMPERATURE TEST SETUP AND TEST PROCEDURE

The test setup shown in figure 2 consisted of the following:

a. The four-circuit breaker load center was of a type suitable for service entrance usage. The 20 A circuit breakers were wired with #12 AWG solid copper TW insulated wire[1].

b. The measuring junction of a copper/constantan (type T) thermocouple formed from 0.020-inch diameter thermocouple wire was placed in contact with the circuit breaker wire binding screw.

c. The thermocouple output was read on a digital voltmeter.

d. The reference junction of the thermocouple was maintained at 32°F in a Dewar containing a mixture of ice and water.

The millivolt thermocouple readings were converted to temperature in degrees Fahrenheit based on NBS Monograph 125 [8].

e. Low voltage current was impressed on the circuit breaker or fuse by means of a current controller, a motor-driven autotransformer, and a 5 KVA step-down transformer having a 120 V primary winding and a 12 V secondary winding.

f. Current was measured by recording the voltage drop across a 0.001 ohm ± 0.05%, 500 A, AC shunt.

g. The digital voltmeter was connected to a double-pole double-throw toggle switch for measuring either circuit breaker temperature or current.

h. The circuit breaker or fuse and load centers were placed in their normal wall-mounted position within a small environmental chamber having a temperature range capability of +350°F to -120°F with a specified control tolerance of ± 1/4°F. The work space was 16 inches wide, 12 inches high, and 11 inches deep. The chamber had its own temperature indicator.

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[1] TW wire insulation has a 60° C maximum operating temperature rating

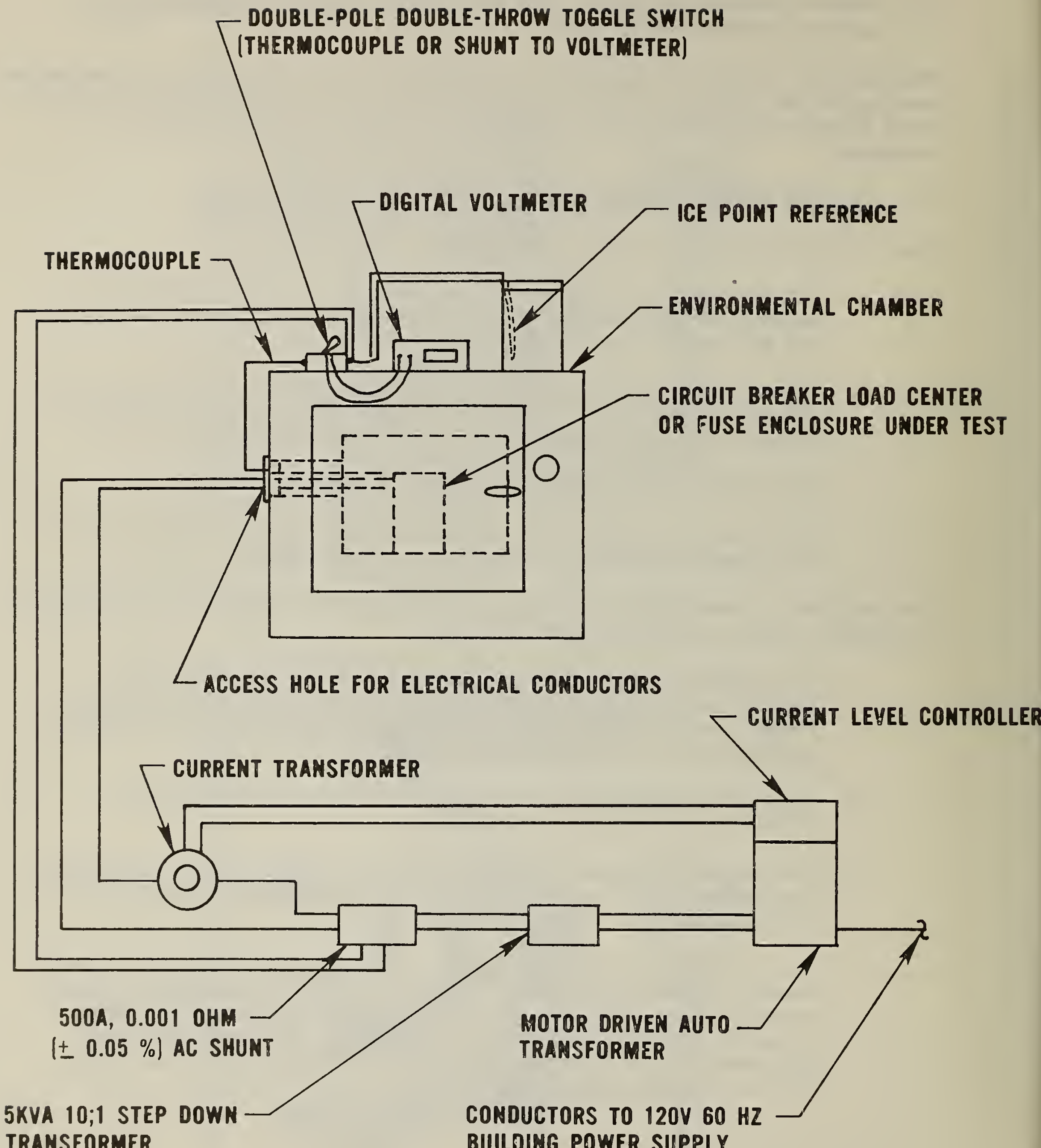

Figure 2. Test setup for temperature performance of breakers and fuses

i. Electric timers were used for timing overcurrent device trips. In case of very fast trips a storage-type oscilloscope was connected across the AC shunt mentioned in (f) above.

The test procedure consisted of the following:

a. Single-pole, 20 A, molded-case circuit breakers of two manufacturers were used in this work. (See table 1). Three of these breakers had been used in other tests involving several hundred short circuits with currents in excess of 500 A rms (root mean square), with a building supply voltage of 118 volts. Other breakers were new (as received from the vendor).

b. The autotransformer was adjusted for proper current setting.

c. When the temperature established within the environmental chamber was measured on the wire binding screw of the circuit breaker, the current was impressed on the breaker and the timer was started. When the breaker tripped, the timer was shut off, recording the time to trip.

The test setup of figure 2 was for only one circuit breaker or one fuse. It is conceivable that a residence may have only one circuit operating at a given time. However, circuit-breaker load centers usually involve combinations of breakers, some carrying current and some not. Current-carrying breakers and wiring contribute heat to the circuit breaker load center, which elevates the temperatures of other breakers. The test setup of figure 3 was used for determining the influence of heat from additional breakers on breaker tripping performance. The load center containing three breakers was mounted in the chamber shown in figure 2. The load center was identical to that used in figure 2. The setup of figure 3 uses an additional autotransformer, step-down transformer, 0.001 ohm AC shunt and digital meter to measure and control current in the circuit breaker specimens #5 and #6. Circuit breaker specimens #5 and #6 were operated at 0-18 A in order to supply additional heat and observe whether breaker #1 would trip when subjected to 27 A with relatively low ambient air temperature. Temperature was measured only on breaker #1. The voltage drops across circuit breakers and currents through them were used to indicate the heating effect of each breaker.

2.2 TEST RESULTS FOR SINGLE CIRCUIT-BREAKERS

Circuit breaker specimen # 1 was tested over the temperature and current range shown in table 2. Since circuit breaker #1 did trip satisfactorily over the range of temperature and currents of table 2, the breaker was subjected to other currents and temperatures, presented in table 3. As this test shows, the breaker usually did not trip. Run number 6 was a check on breaker performance at 135 percent of rated current similar to the calibration test in UL Standard 489 [3]. The breaker passed this calibration test. At the end of the 4.5-hour run #8 in table 3, the current was increased to 28 A, shown in the table as run #9. At the end of run #9 without the circuit

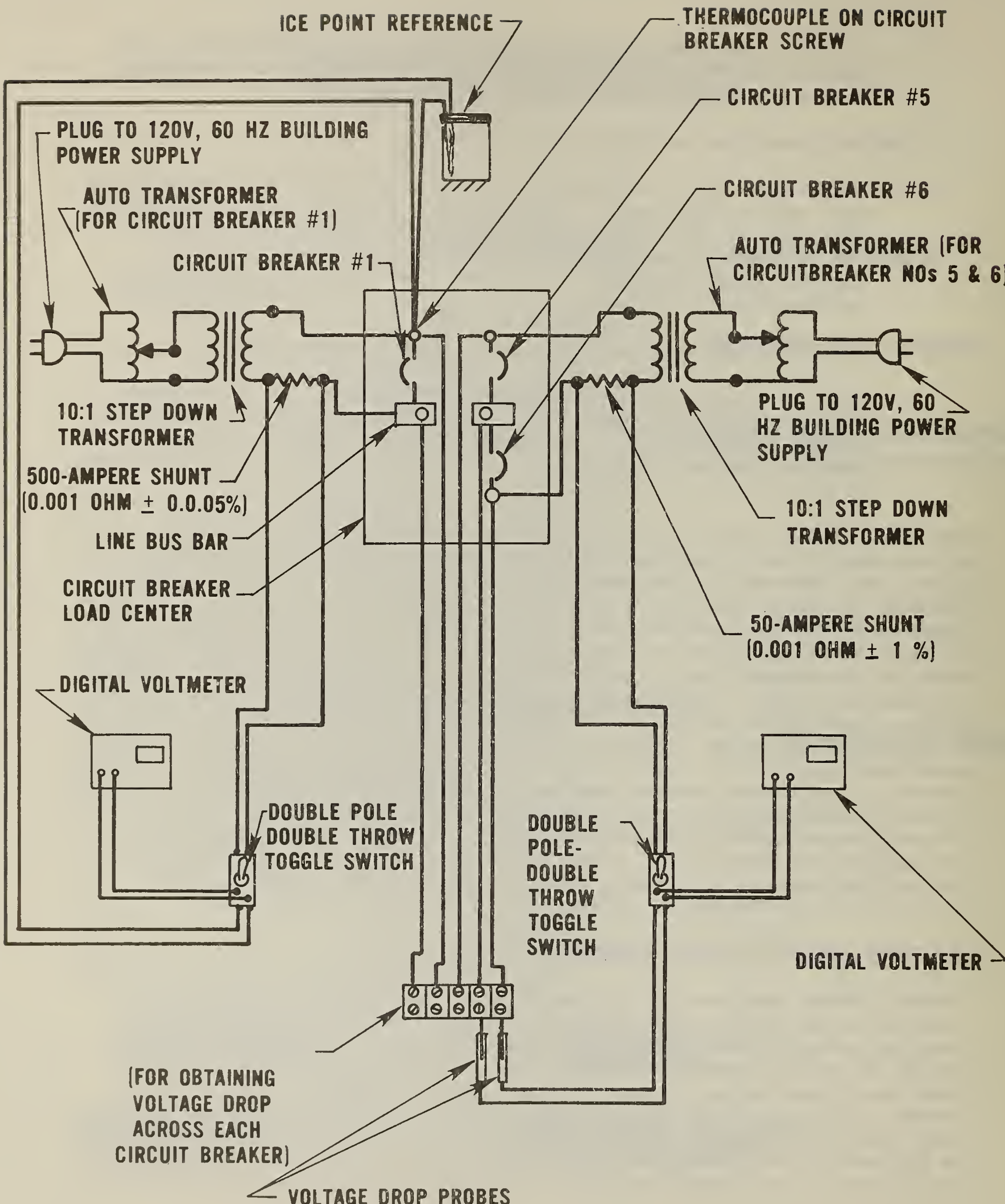

Figure 3. Multi-circuit-breaker test setup

TABLE 1. Circuit Breaker and Fuse Test Specimen

Circuit Breakers:	Manufacturer A Specimen No.	Manufacturer B Specimen No.
	1 (used)	6 (new)
	2 "	7 "
	3 "	8 "
	4 (new)	9 "
	5 "	

Fuses: 30 standard 20 A plug fuses of one manufacturer.

TABLE 2. Performance of Circuit Breaker #1 Over Extreme Temperature Range

		AMBIENT AIR TEMPERATURE AND CIRCUIT BREAKER TRIP TIME - SEC.									
RUN		150°F	104°F	77°F	50°F	32°F	0°F	-10°F	-20°F	-30°F	-40°F
1	70 A	3.85	5.3	6.0	6.8	8.3	8.4	9.4	9.9	12.0	17.0
2		3.89	5.84	6.1	6.6	8.6	9.4	9.8	11.9	11.3	17.8
4	60 A	4.7	8.20	9.2	10.4	12.7	14.3	14.7	15.0	16.0	17.5
5		5.8	7.7	8.0	10.7	12.9	14.2	15.5	16.0	17.7	17.0
5	50 A	7.2	12.0	14.2	16.5	23.9	26.7	27.6	29.2	27.7	30.0
6		7.1	11.76	14.8	16.9	24.5	27.8	27.8	32.7	28.0	30.0
7	40 A	11.9	22.0	30.0	42.7	54.8	81.6	80.3	32.7	99.4	125.8
8		12.0	22.8	28.9	37.4	57.5	105	76.0	193	90.8	126.8
9	27 A	59.7	24.24	76.8							
10		34.5	34.3	406							

TABLE 3. Test of Circuit Breaker #1 Over the Current Range 24 A to 29 A Within the Temperature Range 36°F to 77°F

Run #	Ambient Temperature °F	Current Amperes	Trip	Run Time Hours	Run Time Seconds
1	39	25	No	3.5	
2	36	27	No	3.5	
3	41	27	No	6.7	
4	50	27	No	5.5	
5	60	27	No	5.0	
6	77	27	Yes		972
7	77	24	No	1.5	
8*	61	27	No	4.5	
9*	61	28	No	2.5	
10*	61	29	Yes		10.8

* consecutive runs

breaker tripping, the current was increased to 29 A. As shown, the circuit breaker tripped in 10 seconds.

Circuit breaker #2 was tested over the temperature range 39°F to 77°F and at currents of 25 A and 27 A, as shown in table 4. The circuit breaker tripped during all runs.

Circuit breaker #3 was tested over the temperature range 49°F to 77°F and the current range from 27 A to 40 A. Results are shown in table 5. The circuit breaker did not trip at 27 A and 49°F during one run out of three. During the one run at 25 A and 49°F, the circuit breaker did not trip. The circuit breaker did not trip during the run at 24 A and 59°F. During one run at 25 A and 77°F, the circuit breaker tripped; during a following run at 25 A and 78°F the circuit breaker did not trip.

Results for circuit breaker #4 are shown in table 6. The circuit breaker did not trip during runs #7 and #9 at 27 A and 45°F ambient temperature. However, during run #8 when the current was increased by one ampere to 28 A, the circuit breaker tripped in 591 seconds.

Circuit breaker specimens #5 and #6 were spot checked at 27 A and 45°F. These circuit breakers did not trip during 6-hour runs.

Table 7 shows that breaker specimen #7 always tripped at 27 A and 44°F ambient temperature. At 25 A the circuit breaker tripped during run #4 in about twenty minutes; however, in repeating run #4 as run #5, the breaker did not trip.

Results for the test of circuit breaker #8 are shown in table 8. The circuit breaker had not tripped at the end of run #5 at 25 A and 44°F and at that time the current was increased to 26 A without tripping the circuit breaker during an additional three-and one-half hours as run #6.

Table 9 gives results for the test of circuit breaker #9. The circuit breaker tripped at 26 A and 44°F. The circuit breaker did not trip at 27 A and 32°F.

2.3 TEST RESULTS FOR FUSES

Tables 10 and 11 show results for standard 20 A plug fuses. These were tested over the temperature range 30°F to 77°F and current range 22 A to 40 A. At 22 A and 23 A and 44°F, fuses did not blow. The 44°F ambient temperature data of table 10 shows that fuse currents had to be reduced to 22 or 23 A to prevent fuses from blowing. Comparison of the data in tables 10 and 11 shows that a reduction in the ambient temperature from 77°F to 31°F almost doubled the time for a fuse to open the circuit when carrying 27 A.

Tables 7 and 8 show that circuit breakers would not trip when carrying 25 A when the ambient temperature was 44°F. Fuses in table 10 show better performance than circuit breakers at this temperature. These fuses blew at 24 and 25 A.

TABLE 4. Test of Circuit Breaker #2 at 25 A and 27 A Within the Temperature Range 39°F to 77°F

Run #	Ambient Temperature °F	Current Amperes	Trip	Run Time Seconds
1	59	27	Yes	204.2
2	54	27	Yes	239
3	54	25	Yes	2280
4	39	27	Yes	611
5	39	25	Yes	3540
6	77	25	Yes	410
7	77	25	Yes	481
8	77	25	Yes	285
9	77	27	Yes	100
10	77	27	Yes	231.4
11	77	27	Yes	121.7
12	77	27	Yes	155.1

TABLE 5. Test of Circuit Breaker #3 over Current Range 24 A to 40 A and Temperature Range 49°F to 78°F

Run #	Ambient Temperature (°F)	Current (Amperes)	Trip	Run Time (Seconds)	Run Time (Hours)
1	59	27	Yes	399.2	
2	59	24	No		4
3	59	25	Yes	802	
4	49	27	No		2
5	49	27	Yes	415	
6	49	27	Yes	1009	
7	49	25	No		7
8	77	25	Yes	1620	
9	78	25	No		2
10	77	27	Yes	180	
11	77	27	Yes	444	
12	77	27	Yes	180	
13	77	40	Yes	20	
14	77	40	Yes	15	
15	77	40	Yes	23	
16	77	40	Yes	23	
17	77	40	Yes	22	

TABLE 6. Test of Circuit Breaker #4 over Current Range 27 A to 40 A and Temperature Range 44°F to 77°F

Run #	Ambient Temperature (°F)	Current Amperes	Trip	Run Time (Seconds)	Run Time (Hours)	Temperature/ Screw
1	77	27	Yes	950		
2	77	27	Yes	1403		
3	77	27	Yes	982		
4	77	40	Yes	28		
5	77	40	Yes	25		
6	77	40	Yes	28		
7	44	27	No		3.7	
8	45	28	Yes	591		91
9	45	27	No		4	95

TABLE 7. Test of Circuit Breaker #7 over Current Range 25 A to 40 A and Temperature Range 44°F to 77°F

Run #	Ambient Temperature (°F)	Current (Amperes)	Trip	Run Time (Seconds)	Run Time (Hours)
1	44	27	Yes	472	
2	44	27	Yes	360	
3	45	27	Yes	400	
4	44	25	Yes	1307	
5	44	25	No		2.7
6	77	27	Yes	210	
7	77	27	Yes	211	
8	77	27	Yes	234	
9	77	27	Yes	240	
10	77	40	Yes	30	
11	77	40	Yes	24	
12	77	40	Yes	32	
13	77	40	Yes	33	
14	77	40	Yes	31	
15	77	40	Yes	31	

TABLE 8. Test of Circuit Breaker #8 over Current Range 25 A to 27 A and Temperature Range 32°F to 44°F

Run #	Ambient Temperature (°F)	Current (Amperes)	Trip	Run Time (Seconds)	Run Time (Hours)
1	43	27	Yes	561	
2	44	27	Yes	515	
3	44	27	Yes	619	
4	44	25	No	2460	
5	44	25	No		4.3
6	44	26	No		3.5
7	32	27	Yes	672	
8	32	27	Yes	556	
9	32	27	Yes	610	
10	32	26	Yes		1.1

TABLE 9. Test of Circuit Breaker #9 over Current Range 26 A to 40 A and Temperature Range 32°F to 77°F

Run #	Ambient Temperature (°F)	Current Amperes	Trip	Run Time (Seconds)	Run Time (Hours)
1	44	26	Yes	1179	
2	44	26	Yes	3517	
3	32	27	No		6.5
4	77	27	Yes	288	
5	77	27	Yes	307	
6	77	27	Yes	297	
7	77	40	Yes	37	
8	77	40	Yes	36	
9	77	40	Yes	37	

TABLE 10. Test of Standard 20 A Plug Fuses over Current Range 23 A to 27 A and Temperature Range 31°F to 44°F

Fuse #	Ambient Temperature (°F)	Current (Amperes)	Opened Circuit	Run Time (Seconds)	(Hours)
1	43	26	Yes	146	
2	43	25	Yes	338	
3	43	24	Yes	1708	
4	44	24	Yes	765	
5	44	23	No		2.5
6	44	23	Yes	554	
7	44	22	No		5.3
8	44	26	Yes	167	
9	44	25	Yes	332	
10	44	24	Yes	1530	
11	44	23	No		1.4
12	44	23	No		4.2
13	31	27	Yes	93	
14	31	27	Yes	84	
15	31	27	Yes	77	
16	33	27	Yes	83	

TABLE 11. Test of Standard 20 A Plug Fuses over Current Range 26 A to 40 A at Room Temperature

Fuse #	Ambient Temperature (°F)	Current (Amperes)	Opened Circuit	Run Time Seconds
17	77	26	Yes	52
18	77	26	Yes	94
19	77	26	Yes	89
20	77	26	Yes	90
21	77	26	Yes	73
22	77	27	Yes	38
23	77	27	Yes	54
24	77	27	Yes	48
25	77	27	Yes	43
26	77	27	Yes	44
27	77	40	Yes	2
28	77	40	Yes	2.6
29	77	40	Yes	2.7
30	77	40	Yes	2.6

2.4 MULTI-CIRCUIT BREAKER TEST RESULTS

Tables 12A, 12B and 12C show results for circuit breaker specimen #1 tested at 27 A and 49°F ambient air temperature in the same load center with circuit breaker specimens #5 and #6. Specimens #5 and #6 were in series and carried currents of 0, 5, 10, 15, and 19 A. As shown in the tables, circuit breaker #1 did not trip when operated four hours and fifteen minutes with circuit breakers #5 and #6 not carrying current. Circuit breaker #1 did not trip when the circuit breakers #5 and #6 were operating at 15 A or less. However, circuit breaker #1 tripped consistently when circuit breakers #5 and #6 were operated at 19 A. The heat generated by circuit breakers 5 and 6 resulted in a sufficient temperature rise in circuit breaker #1 to cause circuit breaker #1 to trip. The temperature rise at circuit breaker #1 was 35°F when the current in circuit breakers 5 and 6 was increased by 4 amperes. (See run #5 in table 12B and run #1 in table 12C). The total power generated in the circuit breakers with 15 A during run #5 of table 12B was 20 Btu per hour (6 watts) and with 19 A during run #1 of table 12C was 25.6 Btu per hour (7.5 watts). These heat rates were determined from the voltage drop across the circuit breakers and the currents given in the tables.

Table 12A. Test of Breaker #1 Installed in an Enclosure with Breakers #5 & #6 at 49°F Ambient Temperature

Run	Run Time (Minutes)	Breaker Number	Voltage Drop- (mV)	Current- (A)	Breaker #1 Trip Time - (Minutes)	Breaker #1 Screw Temperature (°F)
1	252	1	146.3	27.19	Did not Trip	87
	--	5	0	0	--	--
	--	6	0	0	--	--
2	256	1	146.0	27.07	Did not Trip	85
	"	5	23.5	4.93	--	--
	"	6	23.0	4.93	--	--
	335	1	145.3	27.00	Did not Trip	87
	"	5	23.0	5.06	--	--
	"	6	24.0	5.06	--	--
3	337	1	145.0	26.98	Did not Trip	87
	"	5	47.9	10.04	--	--
	"	6	47.5	10.04	--	--
	389	1	146.1	27.11	Did not Trip	88
	"	5	48.0	9.97	--	--
	"	6	47.7	9.97	--	--

Table 12B. Test of Breaker #1 Installed in an Enclosure with Breakers #5 & #6 at 49°F Ambient Temperature

Run	Run Time (Minutes)	Breaker Number	Voltage Drop-(mV)	Current-(A)	Breaker #1 Trip Time - (Minutes)	Breaker #1 Wire Binding Screw Temperature (°F)
3	409	1	145.8	27.08	Did not Trip	88
	"	5	47.8	9.94	--	--
	"	6	47.5	9.94	--	--
4	412	1	145.9	27.11	Did not Trip	88
	"	5	72.9	14.95	--	--
	"	6	72.6	14.95	--	--
5	466	1	145.4	26.99	Did not Trip	91
	"	5	75.3	15.24	--	--
	"	6	75.1	15.24	--	--
	491	1	146.1	27.10	Did not Trip	91
	"	5	75.6	15.28	--	--
	"	6	75.4	15.28	--	--

Table 12C. Test of Breaker #1 Installed in an Enclosure with Breakers #5 & #6 at 49°F Ambient Temperature

Run	Run Time (Minutes)	Breaker Number	Voltage Drop- (mV)	Current- (A)	Breaker #1 Trip Time - (Minutes)	Breaker #1 Wire Binding Screw Temperature (°F)
1		1	139.8	27.10	30	--
	30	5	96.7	19.05	*	126
		6	97.1	19.05	*	--
2		1	145.7	27.77	6.7	--
	6.7	5	95.2	19.10	*	--
		6	96.1	19.10	*	--
3		1	147.1	27.29	16.7	--
	16.7	5	95.4	19.06	*	--
		6	96.3	19.06	*	--

* Breakers #5 and #6 did not trip

3. CIRCUIT BREAKER PERFORMANCE UNDER SHORT CIRCUIT CONDITIONS

The NEMA standard for molded-case circuit breakers presents data concerning the maximum available short circuit current in service drops* [4]. The data indicate a potential for several thousand amperes of short-circuit current between line and ground. Actual short-circuit current in a particular residence is governed by transformer characteristics, length and wire size, and resistance of the service drop. Examples of NEMA data are given in table 13. The table gives currents in a service drop which was shorted at various distances from distribution transformers [4]. Similar currents could occur in short circuits within service entrance equipment. Therefore, a circuit breaker must be designed to interrupt large short-circuit currents without damage to itself or other elements of the building system. Circuit breakers used in these investigations were rated to interrupt 10,000 A.

The American Electricians' Handbook indicates that there is no easy calculation or accurate predictive approach available for determining short-circuit currents at various points in a given installation [7]. There are unknown factors that must be determined before accurate calculations can be made [7]. One such unknown is circuit impedance.

Within a residence, large short-circuit currents could occur in branch circuits at locations close to the load center. Because of branch circuit conductor resistance, short-circuit currents are smaller at locations farther from the load center. The short-circuit current, line to ground, at the end of the branch circuit in figure 4 would be about 490 A (calculated from Ohm's law.) Of course, short circuits at other positions in the branch could have higher currents. Certain motors or capacitors operating during the time of the short circuit would add some current to the fault and increase the short-circuit current. Based on the above calculations, the magnitudes of short-circuit currents generated under laboratory conditions as presented in this section were chosen as representative for general purpose residential branch circuits.

3.1 SHORT-CIRCUIT TEST SETUP AND TEST PROCEDURE

The laboratory experiments presented in this section were conducted to determine if short circuits caused by nail penetration would be cleared by overcurrent protection devices before ignition of combustibles could occur.

The short-circuit tests used the assembly shown in figure 5 to create the short-circuit. This figure represents the nominal 2" x 4" wooden wall stud. The nail shown in figure 5 was driven through the stud into the cable. The

---

* Service drop: the overhead service conductors from the last pole or other aerial support to and including the splices, if any, connecting to the service-entrance conductors at the building or other structure [1]. See the service drop in figure 4.

Table 13. Symmetrical Single-Phase Short-Circuit Current in Amperes with 120 Volts Line to Ground at Various Distances in #2 AWG 3-Wire Cable from Various Residential Type Distribution Transformers Rated 120/240 Volts

Distance From Transformer (Feet)	Short-Circuit Current, Amperes Transformer Size		
	25 kVA	37.5 kVA	100 kVA
0	8780	13830	35187
5	6927	10904	20845
10	6023	8843	14156
25	4268	5497	7031
50	2835	3318	3792
75	2114	2367	2593
100	1683	1838	1969

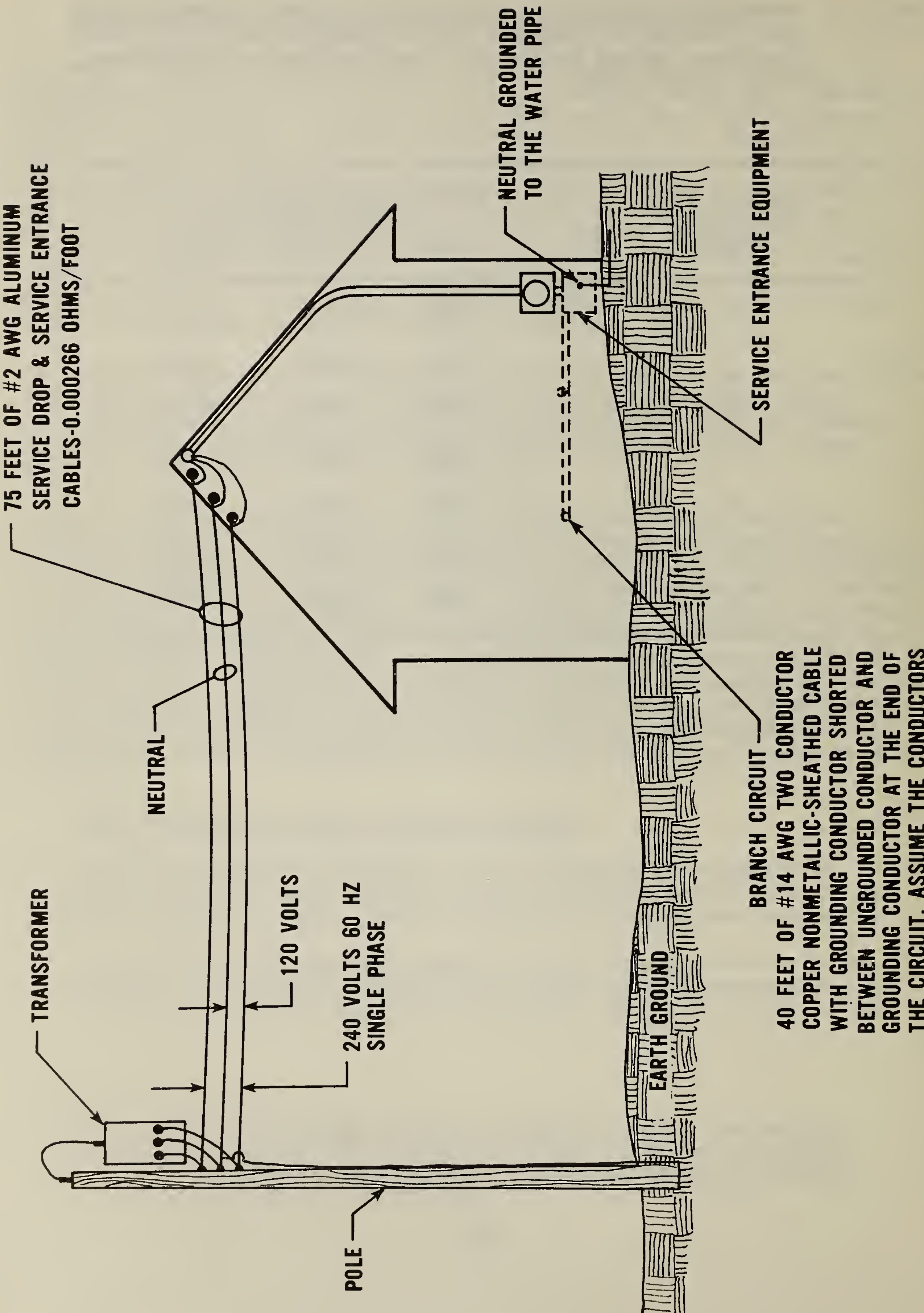

Figure 4. Short circuit in a residence

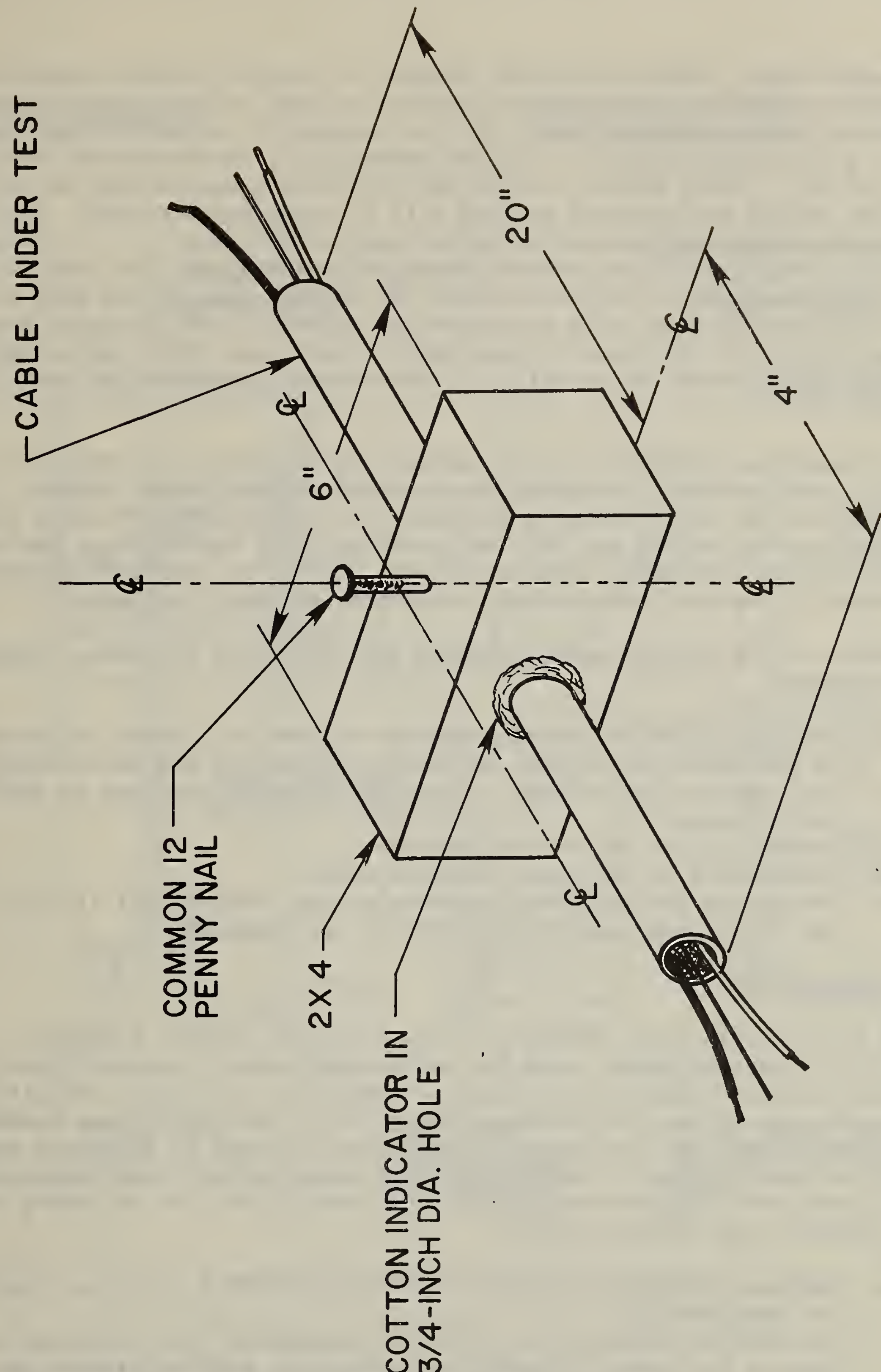

Figure 5. Short circuit specimen

nail made contact (short-circuited) between a current-carrying conductor and grounding conductor. The cotton indicator was used to demonstrate possible ignition of nearby combustibles. The stud appears to be particularly vulnerable to penetration by nails. This vulnerability is considered by article 300-4 (a) (1), "Bored Holes," of the NEC [1] which requires that holes in studs for cables be protected against nail or screw penetrations. That portion of the article concerning studs reads as follows: " . . . holes in studs for cable-type wiring methods shall be bored so that the edge of the hole is not less than 1-1/4 inches from the nearest edge of the stud or shall be protected from nails and screws by either a steel plate or bushing at least 1/16-inch thick and of appropriate length and width installed to cover the area through which nails or screws might penetrate the installed cable."

After installing the short-circuit specimen in the test setup shown in figure 6, the specimen resistance was measured using a kelvin bridge. The resistance of the short could be determined by subtracting the known resistance of specimen wiring and test setup wiring. The initial test specimen temperature was recorded. Surgical cotton, used as an ignition indicator, was packed in the stud hole around the wiring, as shown in figure 5.

Activation of the control switch powered the short; the following information was obtained:

a. Whether or not the circuit breaker tripped and number of cycles of current to trip (time of trip), recorded on the oscilloscope
b. Peak current and voltage - also line voltage, recorded on the oscilloscope.
c. Whether or not cotton was ignited.
d. Temperature on the cable near the short.
e. Whether or not the circuit opened at the shorted nail (if not, the final resistance of the circuit was measured).

3.2 TEST RESULTS

Tables 14A-14H (see pages 30-37) show short circuit results for both nonmetallic-sheathed cable, type NM, and armored cable, type AC. Results show the circuit breaker did not operate during 27 of 64 short-circuit tests. During those tests when the breaker did not trip, the circuit was opened at the conductor and nail interface by "explosive" melting of interface material during the short circuit. Temperature rise above ambient room temperature on the cable near the penetrating nail was about 20°F. The following were also observed from tables 14A-14H:

a. Maximum peak short-circuit currents were 1000 A, the test results in (specimen #2).
b. As shown by specimen #59, initial resistances were sometimes as high as 4.27 ohms. Usually the relatively high resistance was unstable. Resistance variations of $\pm$ 0.5 ohm were observed.
c. The cotton indicators ignited ten times, and in one case the wooden stud was also ignited.

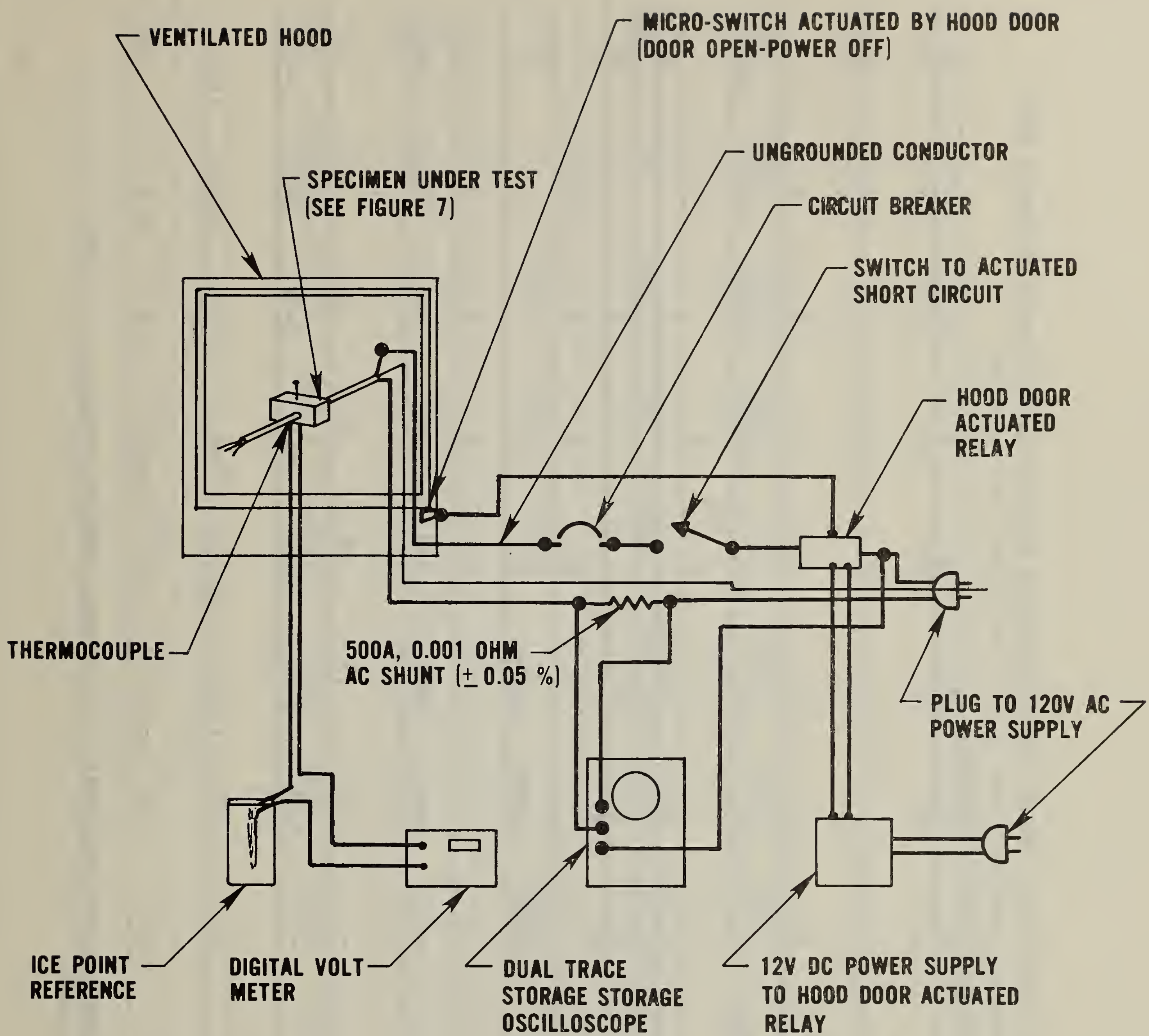

Figure 6. Short circuit test setup

TABLE 14A. Short Circuit Test Results with Simulated 2x4 Stud Section and #12d Common Nail

Specimen No.		1	2	3	4	5	6	7	8
Armored Cable, Type AC					X	X			X
Non Metallic-Sheathed Cable - Type NM		X	X	X			X	X	
Initial Resistance - ohms		-	2.2	1.6	1.2	0.1270	0.2765	0.825	0.406
Cotton Ignited	Yes				X	X		X	
	No	X	X	X			X		X
Cotton Scorched	Yes								
	No	X	X	X			X		X
Breaker Tripped	Yes	X	X	X					X
	No				X	X	X	X	
Final Resistance - ohms		0.1208	0.1208	0.1203	∞	∞	∞	∞	∞
Circuit Opened					X	X	X	X	X
Peak Amperes - A		-	1000	1000	800	800	800	750	900
Peak Volts During Short Circuit - V		-	75	75	78	77	75	95	96
Clear Time-Seconds		-	0.08	0.13	0.01	0.13	0.02	0.01	0.14
Initial Wire Temperature Near Nail - °F		-	79	79.5	78.7	79.8	78.7	78.7	79.6
Final Wire Temperature Near Nail - °F		-	82	82.7	78.7	82.7	79.6	81.8	87

Test circuit resistance (no specimen attached) = 0.1135 ohms, ambient temperature = 75°F, line voltage = 166 volts peak.

TABLE 14B. Short Circuit Test Results with Simulated 2x4 Stud Section and #12d Common Nail

Specimen No.		9	10	11	12	13	14	15	16
Armored Cable, Type AC					X	X	X	X	X
Non Metallic-Sheathed Cable, Type NM		X	X	X					
Initial Resistance - ohms		0.3250	0.1291	0.151	0.1410	0.4499	0.1328	0.1270	0.152
Cotton Ignited	Yes			X				X	
	No	X	X		X	X	X		X
Cotton Scorched	Yes		X	X				X	
	No	X			X	X	X		X
Breaker Tripped	Yes	X			X	X	X		X
	No		X	X				X	
Final Resistance - ohms		0.1203	∞	∞	0.1241	0.1236	0.1274	∞	0.123
Circuit Opened			X	X				X	
Peak Amperes - A		800	900	800	900	800	900	600	900
Peal Volts During Short Circuit - V		75	75	85	76	75	76	100	75
Clear Time-seconds		0.13	0.07	0.08	0.14	0.14	0.14	0.017	0.13
Initial Wire Temperature Near Nail - °F		78.7	79.1	79.1	77	77.8	78.2	79.6	77.8
Final Wire Temperature Near Nail - °F		83.5	95.8	98.8	86.6	84.4	83.5	81.3	87.9

Test Circuit Resistance (No Specimen Attached)
Equaled 0.1135 ohms, Ambient Temperature was 75°F, Line Voltage 166 Volts Peak

Table 14C. Short Circuit Test Results with Simulated 2x4 Stud Section and #12d Common Nail

Specimen No.		17	18	19	20	21	22	23	24
Armored Cable, Type AC		X	X			X			X
Non Metallic-Sheathed Cable, Type NM				X	X		X	X	
Initial Resistance - ohms		0.1341	0.1260	0.4997	0.1460	0.1240	0.55	2.4	0.207
Cotton Ignited	Yes						X		
	No	X	X	X	X	X		X	X
Cotton Scorched	Yes			X			X	X	
	No	X	X		X	X			X
Breaker Tripped	Yes	X	X		X	X			X
	No			X			X	X	
Final Resistance - ohms		0.1240	0.1240	∞	0.1210	0.1237	∞	∞	0.1239
Circuit Opened				X			X	X	
Peak Amperes - A		900	900	800	--	1000	700	600	1000
Peak Volts During Short Circuit - V		76	75	90	--	76	95	99	75
Clear Time-Seconds		0.12	0.12	0.040	--	0.13	0.03	0.01	0.14
Initial Wire Temperature Near Nail - °F		80.5	77	78.3	78.3	77	77.8	77.8	79.6
Final Wire Temperature Near Nail - °F		85.7	86	81.8	81.3	78.5	--	81.3	84.9

Test Circuit Resistance (No Specimen Attached)
Equaled 0.1135 ohms, Ambient Temperature was 75°F, Line Voltage 166 Volts Peak

TABLE 14B. Short Circuit Test Results with Simulated 2x4 Stud Section and #12d Common Nail

Specimen No.		9	10	11	12	13	14	15	16
Armored Cable, Type AC					X	X	X	X	X
Non Metallic-Sheathed Cable, Type NM		X	X	X					
Initial Resistance - ohms		0.3250	0.1291	0.151	0.1410	0.4499	0.1328	0.1270	0.152
Cotton Ignited	Yes			X				X	
	No	X	X		X	X	X		X
Cotton Scorched	Yes		X	X				X	
	No	X			X	X	X		X
Breaker Tripped	Yes	X			X	X	X		X
	No		X	X				X	
Final Resistance - ohms		0.1203	∞	∞	0.1241	0.1236	0.1274	∞	0.123
Circuit Opened			X	X				X	
Peak Amperes - A		800	900	800	900	800	900	600	900
Peal Volts During Short Circuit - V		75	75	85	76	75	76	100	75
Clear Time-seconds		0.13	0.07	0.08	0.14	0.14	0.14	0.017	0.13
Initial Wire Temperature Near Nail - °F		78.7	79.1	79.1	77	77.8	78.2	79.6	77.8
Final Wire Temperature Near Nail - °F		83.5	95.8	98.8	86.6	84.4	83.5	81.3	87.9

Test Circuit Resistance (No Specimen Attached)
Equaled 0.1135 ohms, Ambient Temperature was 75°F, Line Voltage 166 Volts Peak

Table 14E. Short Circuit Test Results with Simulated 2x4 Stud Section and #12d Common Nail

Specimen No.		33	34	35	36	37	38	39	40
Armored Cable, Type AC							X	X	X
Non Metallic-Sheathed Cable, Type NM		X	X	X	X	X			
Initial Resistance - ohms		0.3150	0.1530	0.1269	0.3955	2.49	0.1213	0.1230	0.121
Cotton Ignited	Yes								
	No	X	X	X	X	X		X	X
Cotton Scorched	Yes	X		X			X		
	No		X		X	X		X	X
Breaker Tripped	Yes		X		X			X	X
	No	X		X		X	X		
Final Resistance - ohms		∞	0.1192	∞	∞	∞	∞	0.1230	0.1195
Circuit Opened		X		X	X	X	X		
Peak Amperes - A		650	800	800	900	600	650	700	700
Peak Volts During Short Circuit - V		80	75	80	75	90	100	70	70
Clear Time-Seconds		0.01	0.13	0.04	0.13	0.03	0.03	0.14	0.03
Initial Wire Temperature Near Nail - °F		76.5	76.5	77	76.9	77	77	77.8	77
Final Wire Temperature Near Nail - °F		--	--	--	81.9	80.9	82.7	83.5	81.3

Test Circuit Resistance (No Specimen Attached)
Equaled 0.1135 ohms, Ambient Temperature was 75°F, Line Voltage 166 Volts Peak

Table 14F. Short Circuit Test Results with Simulated 2x4 Stud Section and #12d Common Nail

Specimen No.		41	42	43	44	45	46	47	48
Armored Cable, Type AC		X	X	X	X	X	X	X	X
Non Metallic-Sheathed Cable, Type NM									
Initial Resistance - ohms		0.1205	0.1211	0.206	1.05	0.1157	0.1284	0.1254	0.1283
Cotton Ignited	Yes								
	No	X	X	X	X	X	X	X	X
Cotton Scorched	Yes								
	No	X	X	X	X	X	X	X	X
Breaker Tripped	Yes	X	X	X		X	X	X	X
	No				X				
Final Resistance - ohms		0.1188	0.1198	0.1322	∞	0.1196	0.1229	0.1234	0.1355
Circuit Opened					X				
Peak Amperes - A		700	700	600	750	900	900	--	800
Peak Volts During Short Circuit - V		70	70	70	70	75	75	--	75
Clear Time-Seconds		0.14	0.13	0.14	0.02	0.13	0.13	--	0.13
Initial Wire Temperature Near Nail - °F		77.8	76.9	76.5	76.9	77	77	80.5	76.9
Final Wire Temperature Near Nail - °F		82.7	81.8	81.8	82.7	80.9	82.7	84.4	84.4

Test Circuit Resistance (No Specimen Attached)
Equaled 0.1135 ohms, Ambient Temperature was 75°F, Line Voltage 166 Volts Peak

Table 14G. Short Circuit Test Results with Simulated 2x4 Stud Section and #12d Common Nail

Specimen No.		49	50	51	52	53	54	55	56
Armored Cable, Type AC		X	X	X					
Non Metallic-Sheathed Cable, Type NM					X	X	X	X	X
Initial Resistance - ohms		0.1264	0.1248	0.1250	0.1306	3.855	0.1255	0.335	0.243
Cotton Ignited	Yes					X			
	No	X	X	X	X		X	X	X
Cotton Scorched	Yes		X			X		X	X
	No	X		X	X		X		
Breaker Tripped	Yes	X		X	X				
	No		X			X	X	X	X
Final Resistance - ohms		0.1253	∞	0.1243	0.1195	∞	∞	∞	∞
Circuit Opened			X			X	X	X	X
Peak Amperes - A		800	700	850	900	500	500	800	700
Peak Volts During Short Circuit - V		75	75	75	75	85	--	99	99
Clear Time-Seconds		0.13	0.03	0.13	0.13	0.03	0.01	0.02	0.01
Initial Wire Temperature Near Nail - °F		81.3	78.3	76.9	76	73.4	74.3	75.2	76.
Final Wire Temperature Near Nail - °F		88.8	78.3	84.4	80	--	76.9	80	77.

Test Circuit Resistance (No Specimen Attached)
Equaled 0.1135 ohms, Ambient Temperature was 75°F, Line Voltage 166 Volts Peak

Table 14H. Short Circuit Test Results with Simulated 2x4 Stud Section and #12d Common Nail

Specimen No.		57	58	59	60	61	62	63	64
Armored Cable, Type AC						X			
Non Metallic-Sheathed Cable, Type NM		X	X	X	X		X	X	X
Initial Resistance - ohms		0.1428	0.1544	4.27	0.167	0.1240	0.1301	0.1295	0.1217
Cotton Ignited	Yes	X							
	No		X	X	X	X	X	X	X
Cotton Scorched	Yes	X		X	X				
	No		X			X	X	X	X
Breaker Tripped	Yes		X				X	X	X
	No	X		X	X	X			
Final Resistance - ohms		∞	0.1439	∞	∞	∞	0.1205	0.1215	0.1170
Circuit Opened		X		X	X	X			
Peak Amperes - A		800	900	800	700	800	800	800	800
Peak Volts During Short Circuit - V		75	75	80	85	100	76	75	80
Clear Time-Seconds		0.03	0.13	0.13	0.01	0.01	0.14	0.13	0.03
Initial Wire Temperature Near Nail - °F		78.7	78.3	76.9	76.9	77.8	76.9	76	76
Final Wire Temperature Near Nail - °F		83.5	79.1	--	--	78.3	--	78	76.5

Test Circuit Resistance (with no Specimen Attached)
Equaled 0.1135 ohms, Ambient Temperature was 75°F, Line Voltage 166 Volts Peak

d. The cotton indicators were scorched 12 times without cotton ignition.

Figures 7, 8, 9 show oscilloscope records of selected short circuits. These figures show current and voltage drop in phase indicating, for all practical purposes, a purely resistive short circuit. Figure 7 shows no apparent current and voltage wave distortion. However, in figures 8 and 9 (for cases when the circuit breaker did not trip) both current and voltage waves were distorted due to sporadic interruption of the current. This may be due to a thermostatting effect that makes and breaks contact between the nail and the wire, thus opening and closing the circuit. Opening and closing on the short circuit in this manner may prevent the circuit breaker from tripping. This is demonstrated by data in figure 9. As shown, the average current during the first cycle was 530 A rms*. No current pulse occurred during the next 6 ms. At the end of the 6 ms period, a current pulse of 350 A rms occurred for a period of 4 ms. At the end of the 4 ms pulse, the current was off for 13 ms. At the end of this off period, a final current pulse of 420 A rms occurred, lasting 8 ms, at which time the circuit opened between the wire and shorting nail. Placing the current pulse data on the circuit breaker curves of figure 10, it is seen that a circuit breaker trip was likely during the 530 A pulse and could not occur during the other pulses.

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* In figure 7, 8, and 9, the current waves have the lowest amplitudes and the voltage waves have the highest amplitudes.

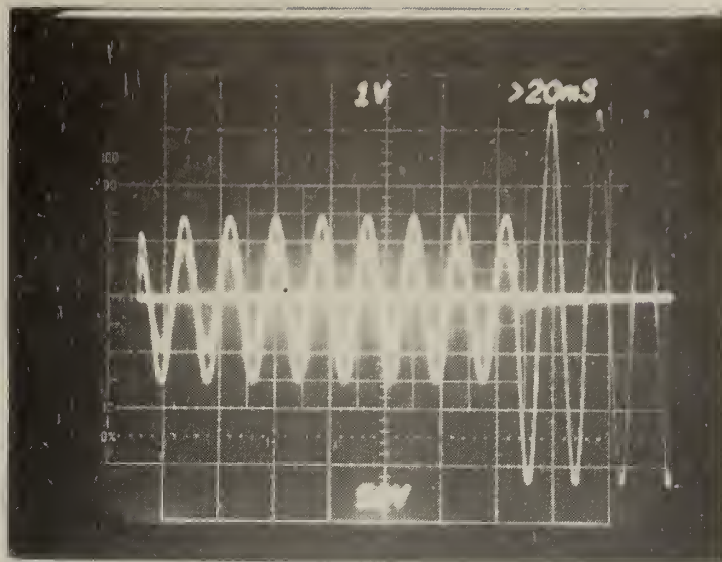

Figure 7. Specimen #3 - circuit breaker tripped during short circuit

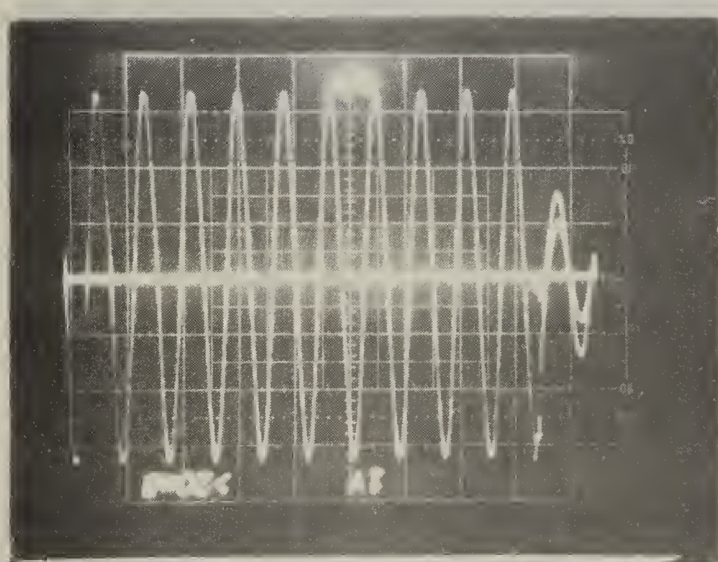

Figure 8. Specimen #6 - circuit breaker did not trip during short circuit

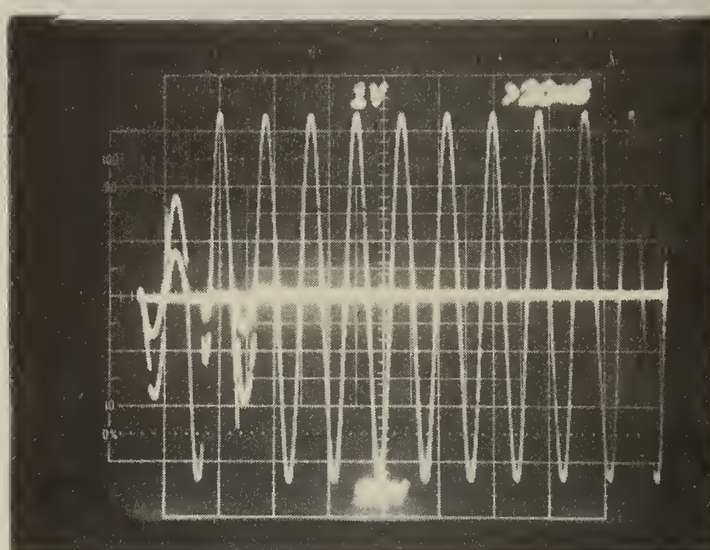

Figure 9. Specimen #19 - circuit breaker did not trip during short circuit

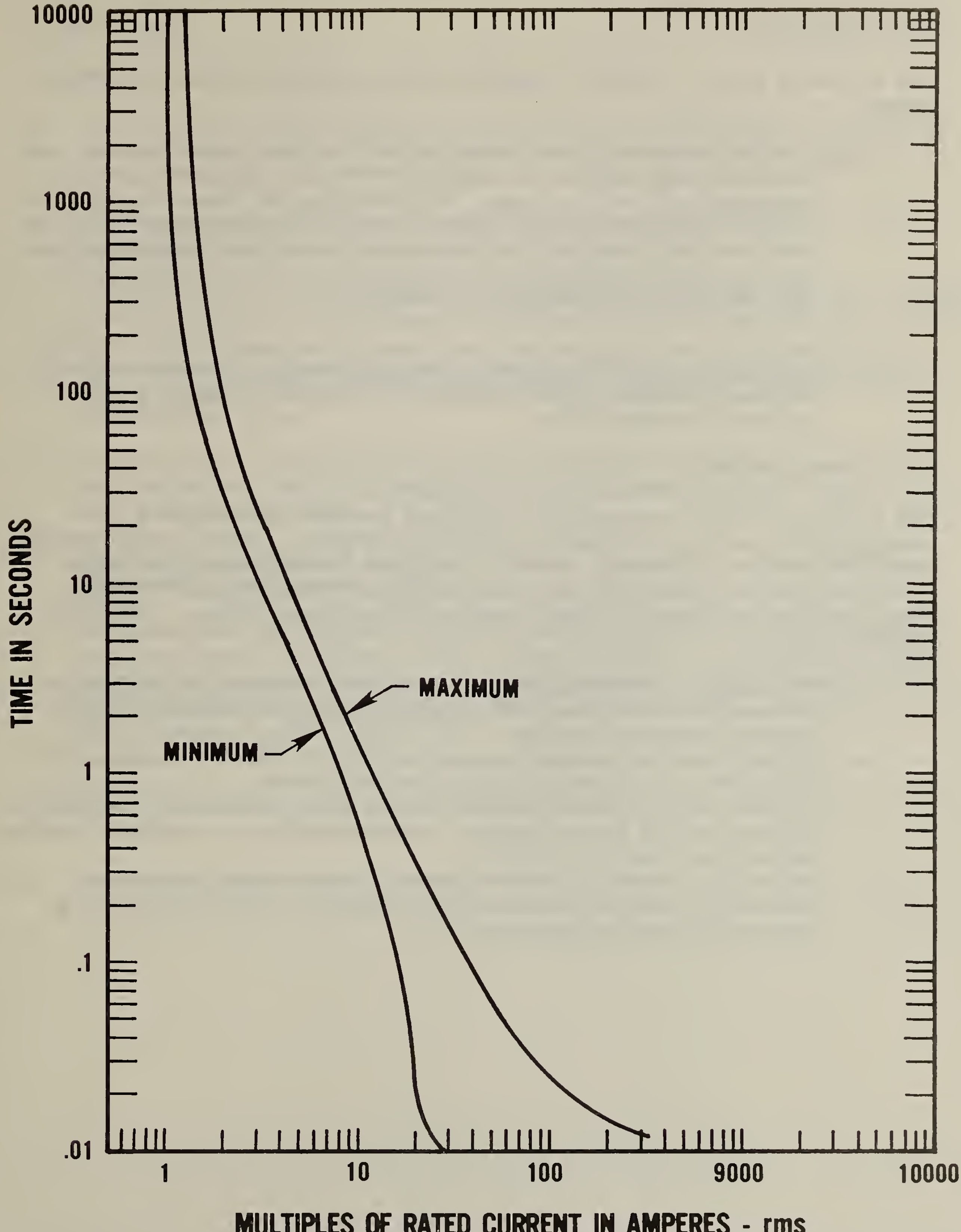

Figure 10. Manufacturer's curves applicable to a 20-ampere circuit breaker

4. CONCLUSIONS

The following can be concluded from this 20 A residential circuit breaker study:

(a) Circuit breakers of the types studied for this report may not trip when carrying currents as large as 28 A when exposed to ambient temperature of 61°F or less. The inability of these circuit breakers to always trip during overcurrents could allow home owners to overload their wiring. Such overloads could cause excessive branch circuit wire temperatures, particularly when the branch circuits are surrounded by thermal insulation [2].

(b) During short circuits which may result from penetration of wiring by nails, circuit breakers of the types studied for this report may not function to interrupt the current and prevent ignition of proximate combustibles.

5. RECOMMENDATIONS

The exploratory data presented in this paper indicate a need for a comprehensive study of overcurrent protection devices. Such a study should yield information concerning potential for fire in residential buildings resulting from the inability of overcurrent protection devices to always open circuits and thereby prevent overheating of fixed wiring. The study should include:

a. Development of more meaningful scientific/mathematical principles and models of the functional characteristics of residential overcurrent protection devices.
b. A field study to measure residential circuit breaker temperature during the winter and during the cooling season.
c. A field study of fires alleged to have been electrically induced, to reconstruct and better explain those mechanisms of electrical system failure that result in fires.
d. Laboratory studies of generic types of residential overcurrent devices on a scale large enough to establish statistical data concerning their performance.

6. REFERENCES

[1] National Electrical Code, 1978, NFPA No. 70-1978.

[2] "Exploratory Study of Temperatures Produced by Self-Heating of Residential Branch Circuit Wiring When Surrounded by Thermal Insulation," Beausoliel, R. W., Meese, W. J., and Galowin, L. S., NBSIR 78-1477, July 1978.

[3] "Molded-case Circuit Breakers and Circuit-breaker Enclosures," UL 489, Underwriter's Laboratories, Inc., November 1, 1972.

[4] "Molded-case Circuit Breakers," Standards Publication No. AB1-1975, National Electrical Manufacturer's Assoc., 155 East 44th St., New York, N.Y. 10017.

[5] "Investigation of Over Current Protection Devices as Affected by Ambient Temperatures," Bulletin of Research, No. 41, July 1948, Underwriter's Laboratories, Inc.

[6] "Procedures for Verifying Performance of Molded-case Circuit Breakers," Publication No. AB2-1976, National Electrical Manufacturer's Assoc., 155 East 44th St., New York, N.Y. 10017.

[7] "American Electricians' Handbook," John H. Watt Editor, Ninth Edition, McGraw-Hill Book Company, 1970.

[8] NBS Monograph 125, "Thermocouple Reference Tables Based on the IPTS-68" by Robert Powell, William J. Hall, Clyde H. Hyink, Jr. and Larry Sparks, Cryogenics Division, Institute of Basic Standards, NBS and George W. Burns, Margaret G. Scroger, and Harmon H. Plumb, Heat Division, Institute for Basic Standards, NBS, March 1974.

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Laboratory test results show that at low ambient temperatures some residential-type circuit breakers may not trip at currents up to 140 percent of rated currents. Under some environmental conditions this may lead to wiring temperatures that exceed the limitations specified in the National Electrical Code. The results also show that circuits sometimes open at the point of short circuits before circuit breakers operate. Ignition of combustibles proximate to the point of such short circuits sometimes occurs.

The results indicate the need for a more detailed study of overcurrent protection performance in the field and under laboratory conditions. Also needed are the development of more meaningful scientific/mathematical principles and models on the functional characteristics of circuit breakers.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

branch circuits; circuit breaker; electrical fire; low ambient temperature; trip time.

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